

Imaging the Shadow of a Supermassive Black Hole: Event Horizon Telescope Observations of Sgr A*

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1. INTRODUCTION

This data delivery contains what is defined by the Event Horizon Telescope Collaboration (EHTC) as L1 data for the Very Long Baseline Interferometry (VLBI) 1-mm 2017 observing campaign by the Event Horizon Telescope (EHT). The 2017 campaign was the first where the Atacama Large Millimeter Array (ALMA) participated as a phased array, a capability that was developed by the ALMA Phasing Project (APP; (Doeleman 2010; Fish et al. 2013; Matthews et al. 2018)). The EHT L1 data encompasses the VLBI correlator output, converted into circular polarization basis, as well as the calibration information from the participating telescopes. For ALMA this includes their quality assurance (QA2) output that is used for the polarization basis conversion. The primary reference for the data from the EHT 2017 April observation campaign is [Event Horizon Telescope Collaboration et al. \(2019a\)](#). The paper in detail discusses the processing carried out for the current L1 data delivery. For scientific results derived from the EHT 2017 April Observation Campaign see <https://eventhorizontelescope.org/publications>. Additional data products derived from this L1 data can be found at <https://eventhorizontelescope.org/for-astronomers/data>.

This data delivery includes data from the following facilities: ALMA, the Atacama Pathfinder Experiment (APEX), the Submillimeter Telescope (SMT), the James Clerk Maxwell Telescope (JCMT), the Large Millimeter Telescope Alfonso Serrano (LMT), the IRAM 30m telescope, the Submillimeter Array (SMA), and the South Pole Telescope (SPT). More information about the facilities used for these observations can be found in [Event Horizon Telescope Collaboration et al. \(2019b\)](#).

The overall goal of the observations is to image the supermassive black holes M87* (M87) and Sagittarius A* (SGRA) at event horizon scales and to image the AGNs OJ287, 3C279, CENA, and NGC1052 at high resolution. The specific goal of the ALMA observations in this project as given in the abstract of the proposal are:

The Galactic Center supermassive black hole, Sagittarius A* (Sgr A*), subtends the largest angular size of any black hole in the universe and is now within the reach of direct imaging with very long baseline interferometry (VLBI). Observations with the Event Horizon Telescope (EHT) have shown that the 1.3mm emission from Sgr A* occurs within 5 Schwarzschild radii of the black hole (Doeleman et al. 2008), but these observations have lacked the sensitivity and baseline coverage to produce images of the emission. We propose Band 6 observations of Sgr A* with ALMA joining the EHT. These observations will produce the first images of a black hole with event-horizon-scale resolution, sufficient to detect distinctive signatures of strong-field gravity such as the “shadow” cast by the supermassive black hole on hot surrounding plasma. They will also produce images of the magnetic field structure near the black hole and will open a new regime of time-domain studies of Sgr A*, allowing us to study a black hole “feeding” in real-time over many orbital periods.

2. CONTENT OF THE DATA DELIVERY

The following file naming conventions have been used throughout the EHT 2017 April Observation Campaign data deliveries:

- `*-fits.tgz`: Final correlation output (FITS)
- `*-hops.tgz`: Final correlation output (HOPS)
- `*-4fit.tgz`: Sample Fourfit Fringe files (4FIT)

- `*-dxin.tgz`: Correlator DiFX input files
- `*-haxp.tgz`: Mixed Pol ALMA-only correlations (HOPS)
- `*-pcin.tgz`: PolConversion input files
- `*-pcqk.tgz`: PolConversion processing artifacts
- `*-swin.tgz`: Correlator DiFX output files (SWIN)
- `*-logs.txt`: Observing track processing logs
- `*.app_deliverables.tgz`: ALMA QA2 data
- `*.metadata-2020-d02-01.tgz`: Observing metadata

Some of these are quite large and have been split into multiple files to get more manageable pieces. These typically group VLBI scans on a single target together. The partition is based on:

- `experiment`: The unique \$EXPER reference label of the VLBI schedule VEX file; typically `e` followed by the last two digits of the year, followed by a track label (`a-z`) followed by two digits of day of month
- `revision`: Revision number; monotonically increasing with time
- `sub-band`: `lo` or `hi` representing the 227.1 GHz and 229.1 GHz bands (representing the band center at ALMA)
- `project`: A short “nickname” corresponding to the primary target of the ALMA project; `na` refers to observations not involving ALMA
- `target`: The name of the target of the VLBI scans

All files are prefixed with the ALMA group uid for the project and an ALMA large project “nickname”. So for example `group.uid_A001_X11b3_X30.ec_eht.e17c07-7-lo-sgra-J1733-fits.tgz` refers to the visibility data in FITS format of the VLBI scans of the SGRA ALMA project that observed target J1733 in track ‘c’ of the EHT observations on April 7th 2017.

The *Correlator DiFX input files* are the control input files for the DiFX software correlator that were used to correlate the data. This includes the correlator model that was used for correlation. This does not include the baseband (voltage) data from the individual telescopes as these have not been retained (as is normal practice for VLBI observations) due to the large size of this data.

The *Correlator DiFX output files* are the raw correlator output in the so-called SWIN format. This data is in mixed polarization basis and is provided to make it possible to redo the conversion into circular polarization basis. The result will have to be converted into FITS or HOPS format using the appropriate tools from DiFX for further processing.

The *PolConversion input files* are the control input files for the `Polconvert` package (Martí-Vidal et al. 2016).

The *PolConversion processing artifacts* provide various diagnostic plots produced by `Polconvert` that provide a means to assess the quality of the conversion from a mixed basis into circular basis.

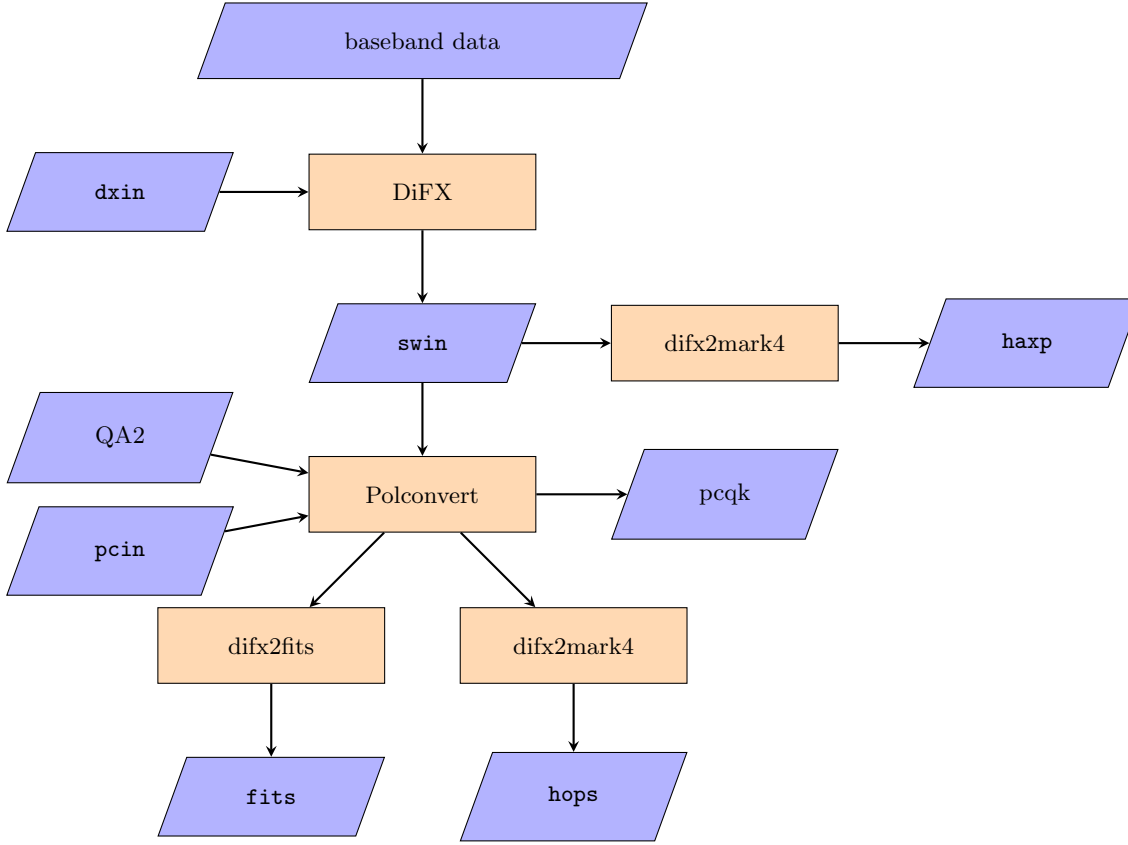
The *Sample Fourfit Fringe files*.

The *Mixed Pol ALMA-only correlations* are a subset of the correlator output in Mk4 fileset (HOPS) format in mixed polarisation basis generated without running `Polconvert`. This subset contains only the files for the baselines that contain ALMA as the files for other baselines have identical content to the ones provided in the *Final correlation output*.

The *Final correlation output* is provided in two different formats: FITS and HOPS. This data is in circular polarization basis. The FITS files follow the FITS-IDI convention as documented in Greisen (2009) and can be loaded into radio-interferometry data reduction software packages like AIPS and CASA. The HOPS files are in the Mk4 fileset format for further processing with the HOPS software package that is often used for mm-VLBI (Whitney et al. 2004).

The *Observing track processing logs* contain output from the top-level data processing and archiving process. These are provided for completeness.

Figure 1. Data processing flow



The *Observing metadata contains* is a collection of metadata to accompany all the EHT Observations taken in April 2017. This includes a priori estimates of station sensitivity for all EHT 2017 scans in ANTAB format (Issaoun et al. 2017), as well as control codes for configuring and reducing EHT data in the CASA and HOPS radio interferometry software environments. Metadata in this package can be used as auxiliary information to process original EHT correlator output in FITS-IDI or HOPS format. Data that has already been reduced and calibrated are provided in accompanying EHT publications, see for example Event Horizon Telescope Collaboration et al. (2019a).

The data processing flow and the data products produced by it are illustrated by figure 1.

3. DATA PROCESSING METHODS

The VLBI baseband data (including ALMA VLBI output) was correlated using the DiFX software correlator (Deller et al. 2011), using zoom bands to account for differences in observation bands and sampling rates used at the various stations that form the EHT. The input parameters for the correlation as well as some of the intermediate parameter descriptions are provided in the `*-dxin.tgz` files. This includes the observed schedule in VEX format (`*.vex.obs`) which includes the clock model and the earth orientation parameters (EOPs) that were used for correlation. The main correlation parameters are provided in the `*.v2d` files. From these files the intermediate parameter files are generated. These are provided in the `*.input` and `*.calc` files. The latter is then used to generate the correlator model, which is provided in the `*.im` files using the CALC11 code bundled with DiFX.

All telescopes of the EHT array, except for ALMA, observed circular polarizations. ALMA instead uses receivers that provide linear polarizations. This results in mixed pol correlation output. This mixed pol output is converted into a circular basis using Polconvert (Martí-Vidal et al. 2016). This was done using the version of Polconvert as bundled with DiFX using the ALMA QA2 data (`*.app_deliverables.tgz`) as auxiliary input (Goddi et al. 2019).

Finally the output from Polconvert is converted into FITS format using the difx2fits tool and converted into HOPS format using the difx2mark4 tool bundled with DiFX.

4. QUALITY ASSESSMENT

Initial quality assessment of the correlated data was performed by an initial fringe-fit using the `fourfit` tool that is part of the HOPS package. These results are included in this data release in the `*-4fit.tgz` package.

Quality assessment of the polarization conversion: `Polconvert` produces diagnostic plots; these plots are included in the `*-pcqk.tgz` files.

The final quality assessment has been done on both the FITS and HOPS data using three different pipelines. This includes fringe validation, checks on thermal error consistency and closure quantities. Details can be found in section 8 of [Event Horizon Telescope Collaboration et al. \(2019a\)](#).

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